Engineering Science and Technology, an International Journal xxx (2015) 1–14

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Engineering Science and Technology, an International Journal

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Full length article

Modeling and optimization of ultrasonic metal welding on dissimilar sheets using fuzzy based genetic algorithm approach

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A R T I C L E I N F O

Article history:
Received 16 January 2015
Received in revised form
17 April 2015
Accepted 17 April 2015
Available online xxx

Keywords:
Ultrasonic metal welding
Fuzzy logic approach
Genetic algorithm
Regression modeling
Weld quality

A B S T R A C T

Ultrasonic welding has been used in the market over the past twenty years and serving to the manufacturing industries like aviation, medical, microelectronics and many more due to various hurdles faced by conventional fusion welding process. It takes very short time (less than one second) to weld materials, thus it can be used for mass production. But many times, the problems faced by industries due to this process are the poor weld quality and strength of the joints. In fact, the quality and success of the welding depend upon its control parameters. In this present study, the control parameters like vibration amplitude, weld pressure and weld time are considered for the welding of dissimilar metals like aluminum (AA1100) and brass (UNS C27000) sheet of 0.3 mm thickness. Experiments are conducted according to the full factorial design with four replications to obtain the responses like tensile shear stress, T-peel stress and weld area. All these data are utilized to develop a non-linear second order regression model between the responses and predictors. As the quality is an important issue in these manufacturing industries, the optimal combinations of these process parameters are found out by using fuzzy logic approach and genetic algorithm (GA) approach. During experiments, the temperature measurement of the weld zone has also been performed to study its effect on different quality characteristics. From the confirmatory test, it has been observed that, the fuzzy logic yields better output results than GA. A variety of weld quality levels, such as "under weld", "good weld" and "over weld" have also been defined by performing micro structural analysis.
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1. Introduction

The ultimate objectives of various sectors like automotive, aircraft, railway transportation, medical, microelectronics etc., are to reduce the weight and energy consumption by introducing new and innovative techniques. To attain these goals, lightweight and high strength materials such as aluminum, titanium, magnesium, copper alloys are necessary. Out of these, aluminum is widely utilized as a part of making fuel cell components in the battery, connecting semiconductor devices, transistors and diodes furthermore in aerospace industry [1,2]. But major barriers of using this material are its high thermal conductivity, joining and its machining cost. So, it is important to pursue for lower cost joining methods. Ultrasonic metal welding (USMW) is one such promising method for joining this type of softer metal. USMW was first developed between the 1940s and 1950s [3] and was first patented in the middle of the 20th century in the USA [4]. The basic applications for USMW include wire bonding in the electronics industry, tube sealing in thermal reactors and thin foil joining. This technique is also appropriate to join dissimilar materials. In the sixties, it was used to join aluminum foils with glass [5]. But the results were not sustained for a long time. So, many of the researchers carried out their research work on aluminum and its alloys using ultrasonic welding.

In USMW, two metal surfaces are joined due to the friction like relative motion between them with a clamping pressure. During this motion, the local surface roughness, contaminants and oxides present over it, deform and disappear and make metal-to-metal contact possible. As this process is a solid state welding process, it occurs without melting of base metal. Generally the ultrasonic vibration is generated in the transducer and transmitted through booster to the sonotrode. The sonotrode is one of the parts of a system that directly touches with the upper part of the specimen and vibrates parallel to the plane of the weld interface and

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Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2015.04.007
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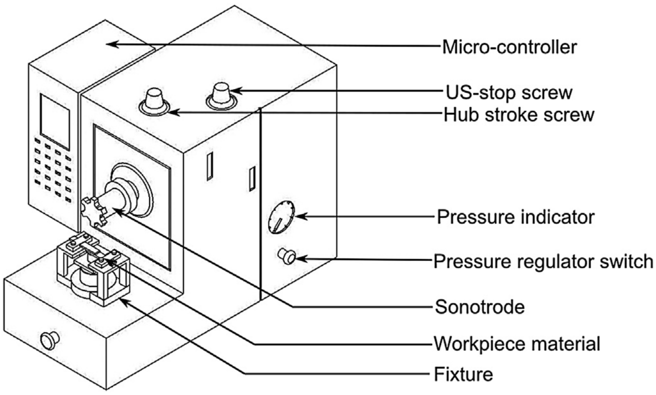

Fig. 1. Schematic diagram of lateral drive ultrasonic welding system.

Table 1
Chemical composition of aluminum (AA1100) and brass (UNS C27000).

Materials	Al	Cu	Mn	Zn	Si	Fe	Other
AA1100-H16	99%	0.05–0.20%	0.05%	0.10%	0.3%	0.3%	0.3%
UNS C27000-H04	–	63–68.50%	–	31.3–37%	–	0.10%	–

perpendicular to the axis of clamping force application. Thus the vibratory energy is transmitted to the weld spot. These spot welds are elliptical in shape at the weld zone and when they are overlapped, they form a continuous weld joint.

The major significance of a sound joint between dissimilar materials like aluminum and brass find its numerous applications in the electrical industries. Generally, copper and brass are utilized extensively in those industries because of its superb electrical and thermal properties, great strength and erosion and fatigue resistances [6]. But as the copper have higher thermal conductivity, thermal expansion and electrical conductivity than brass thus, a larger weld distortion occurs in analogous to brass welds [7]. So, it is more important to examine the weld characteristics of joining of aluminum to brass. In friction stir welding technique, whenever brass was tried to weld with aluminium, hard and brittle intermetallic compounds were formed [8] giving poor weld strength. So, USMW has been believed to be one of the solid state welding processes to overcome this difficulty. Collins et al. [9] did the lap welding experiments by using materials such as aluminum foil and sheet and the relationship among thickness, hardness of the material and the weld strength of the joint was revealed. Tsujino et al. [10] used two oscillation systems simultaneously in multi spot ultrasonic welding system for fabrication of a joint followed by

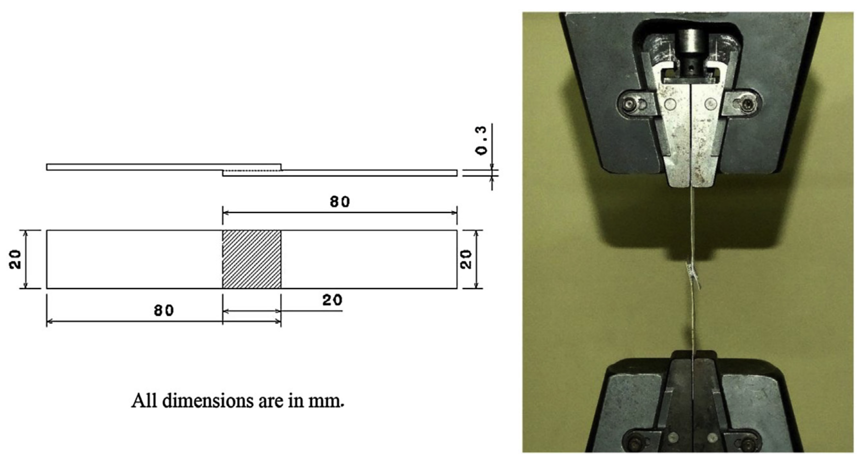

Fig. 2. Lap-shear coupon design and test fixture.

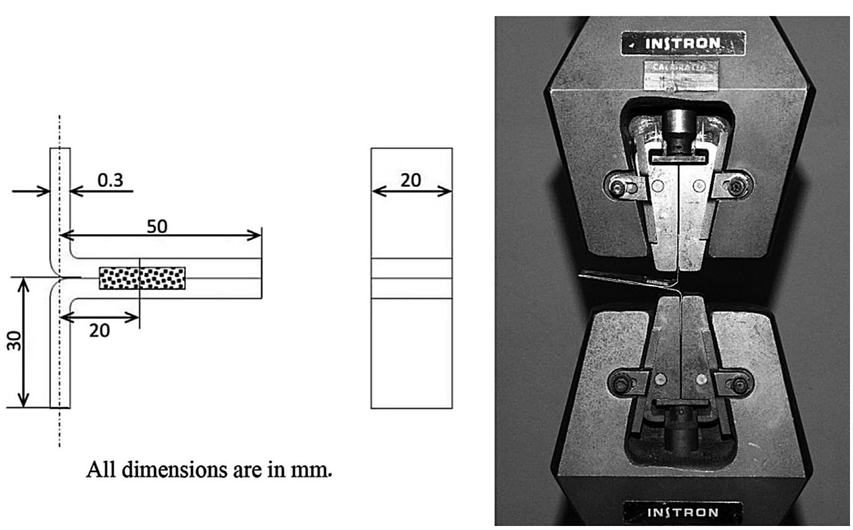

Fig. 3. T-peel coupon design and test fixture.

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Table 2
Important input variables and their levels.

Parameters	Terms	Level 1	Level 2	Level 3	Level 4	Level 5
Amplitude (μm)	A	54	60	68	–	–
Weld pressure (MPa)	P	0.2	0.3	0.4	–	–
Weld time (Sec)	T	0.2	0.4	0.6	0.8	1.0

measurement of joint strength. Furthermore, the effect of the surface oxide layer on the welded joint was inspected by varying the vibration amplitude [11]. The other important aspect of any experiment is its statistical design and it can be developed by using an empirical method. As a matter of fact, the design of experiments was used to conduct experimental campaigns in a few papers. These papers not only explore the interdependence among the input parameters, but also predict the weld strength of welded joints made by USMW. For instance, Elangovan et al. [12] used Taguchi's robust design concept and conducted experimental trials using similar metals like copper. The ANOVA and S/N ratio was also employed to investigate the effect of process parameters on getting maximum weld strength. Fuzzy-logic-based multi-criteria decision making approaches also become very popular in optimization of manufacturing processes. Rupajati et al. [13] optimized the multiple performances like recast layer thickness and surface roughness using fuzzy-logic method with the design of Taguchi L18 mixed-orthogonal array. It was observed that application of this optimization technique significantly improved multiple responses. The same technique was also used to predict the material removal rate

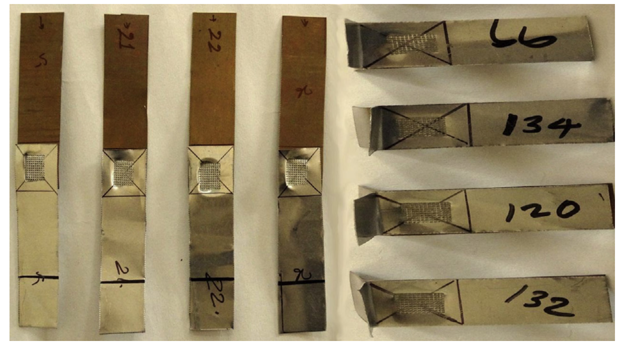

Fig. 4. Tested samples.

Table 3
Experimental results and fuzzy predicted values.

Test runs	Design matrix			Responses			Normalized responses			Fuzzy predicted value
	A (μm)	P (MPa)	T (Sec)	TS (MPa)	TP (MPa)	WA (mm^2)	NTS	NTP	NWA	
1	54	0.2	0.2	0.72	0.41	25.09	0.01	0.00	0.00	0.08
2	54	0.2	0.4	0.93	0.48	37.05	0.08	0.15	0.24	0.17
3	54	0.2	0.6	1.27	0.52	42.10	0.18	0.24	0.34	0.33
4	54	0.2	0.8	1.57	0.58	48.24	0.27	0.37	0.47	0.44
5	54	0.2	1.0	0.68	0.42	55.34	0.00	0.02	0.61	0.30
6	54	0.3	0.2	1.57	0.54	43.20	0.27	0.28	0.37	0.35
7	54	0.3	0.4	2.70	0.69	48.82	0.61	0.61	0.48	0.50
8	54	0.3	0.6	3.22	0.68	50.67	0.77	0.59	0.52	0.65
9	54	0.3	0.8	2.53	0.71	56.25	0.56	0.65	0.63	0.57
10	54	0.3	1.0	2.03	0.50	63.70	0.41	0.20	0.78	0.55
11	54	0.4	0.2	0.83	0.49	40.15	0.05	0.17	0.31	0.23
12	54	0.4	0.4	2.26	0.67	41.00	0.48	0.57	0.32	0.49
13	54	0.4	0.6	1.98	0.64	48.69	0.39	0.50	0.48	0.50
14	54	0.4	0.8	1.85	0.61	52.30	0.35	0.43	0.55	0.49
15	54	0.4	1.0	1.73	0.48	60.39	0.32	0.15	0.72	0.40
16	60	0.2	0.2	0.89	0.50	38.55	0.06	0.20	0.27	0.20
17	60	0.2	0.4	1.01	0.52	44.40	0.10	0.24	0.39	0.33
18	60	0.2	0.6	1.30	0.53	45.54	0.19	0.26	0.41	0.36
19	60	0.2	0.8	1.61	0.58	55.35	0.28	0.37	0.61	0.45
20	60	0.2	1.0	0.78	0.47	58.45	0.03	0.13	0.68	0.35
21	60	0.3	0.2	1.77	0.65	43.77	0.33	0.52	0.38	0.48
22	60	0.3	0.4	3.23	0.74	50.03	0.77	0.72	0.51	0.66
23	60	0.3	0.6	3.39	0.76	52.22	0.82	0.76	0.55	0.71
24	60	0.3	0.8	2.95	0.73	60.18	0.69	0.70	0.71	0.68
25	60	0.3	1.0	2.53	0.66	66.30	0.56	0.54	0.84	0.71
26	60	0.4	0.2	0.95	0.55	43.95	0.08	0.30	0.38	0.45
27	60	0.4	0.4	2.66	0.72	45.65	0.60	0.67	0.42	0.57
28	60	0.4	0.6	2.44	0.67	50.04	0.53	0.57	0.51	0.47
29	60	0.4	0.8	2.07	0.65	56.50	0.42	0.52	0.64	0.54
30	60	0.4	1.0	1.95	0.52	62.10	0.38	0.24	0.75	0.55
31	68	0.2	0.2	1.15	0.50	44.40	0.14	0.20	0.39	0.29
32	68	0.2	0.4	1.10	0.54	50.60	0.13	0.28	0.52	0.40
33	68	0.2	0.6	1.40	0.56	55.45	0.22	0.33	0.62	0.45
34	68	0.2	0.8	1.70	0.58	65.95	0.31	0.37	0.83	0.68
35	68	0.2	1.0	0.85	0.44	68.25	0.05	0.07	0.87	0.48
36	68	0.3	0.2	2.05	0.70	48.95	0.41	0.63	0.48	0.55
37	68	0.3	0.4	3.40	0.78	54.90	0.82	0.80	0.60	0.74
38	68	0.3	0.6	3.99	0.87	58.40	1.00	1.00	0.68	0.76
39	68	0.3	0.8	3.66	0.82	68.80	0.90	0.89	0.89	0.94
40	68	0.3	1.0	2.76	0.74	74.42	0.63	0.72	1.00	0.74
41	68	0.4	0.2	1.69	0.65	46.15	0.31	0.52	0.43	0.49
42	68	0.4	0.4	2.80	0.79	52.45	0.64	0.83	0.55	0.73
43	68	0.4	0.6	2.60	0.76	56.85	0.58	0.76	0.64	0.64
44	68	0.4	0.8	2.25	0.72	67.74	0.47	0.67	0.86	0.72
45	68	0.4	1.0	2.10	0.55	70.53	0.43	0.30	0.92	0.61

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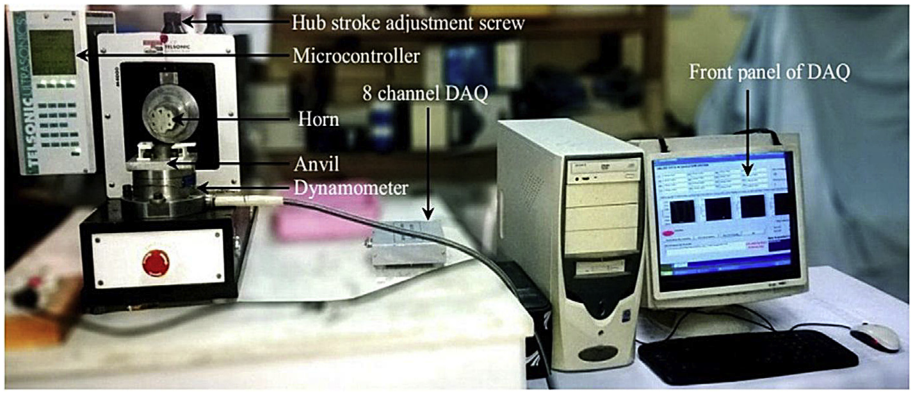

Fig. 5. Ultrasonic metal welding machine setup with DAQ.

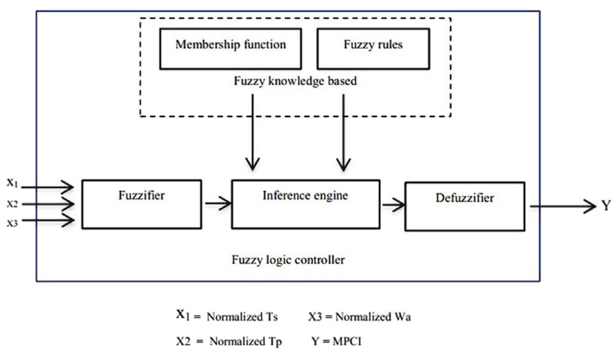

Fig. 6. Three-input-one-output fuzzy logic unit.

Table 4
Fuzzy value ranges for input and output variables.

Parameters	Linguistic values	Fuzzy ranges
Input	S	0–0.3
	M	0.3–0.7
	L	0.7–1.0
Fuzzy multi performance index (FMPI)	VS	0–0.165
	S	0.165–0.385
	M	0.385–0.605
	L	0.605–0.825
	VL	0.825–1.0

(MRR), tool wear rate (TWR) and surface roughness (SR) in ultrasonic-assisted EDM (US/EDM) process [14]. Different other manufacturing processes were also optimized using a similar type of optimization technique [15–17]. Kuruvila et al. [18] investigated the multi objective optimization using GA in which the objective function was defined as the composite function of the responses like DR, SR and MRR and the final objective was expressed as DR + SR − MRR. Other researchers also used same multi objective technique for optimized the machining parameters [19–21].

Now-a-days, as the quality is a vital matter in every manufacturing industry, these should be designed in such a way that it should take less time, less cost and less manpower to produce a high quality product with great accuracy and this can be achieved through process optimization. It is also observed that significant challenges emerge in the welding of aluminum with brass by fusion welding as well as friction stir welding process. Thus, the weldability of brass mostly relies upon the percentage of zinc present in brass. As the zinc has a low boiling temperature, lethal vapours may produce during these kinds of welding processes [1]. In the current study, an effort has been taken to investigate the effects of individual input parameters like amplitude, weld pressure and weld time through USMW on different output parameters such as tensile shear stress, T-peel stress and weld area by using a full factorial design of experiment. Two non-conventional optimization techniques i.e. fuzzy logic and GA have been applied to determine the optimal process parameter conditions at which the outputs are maximized. As in GA, the fitness function requires an equation, a non-linear second order regression model has been developed to find an equation between the input and output variables. Confirmatory tests have been carried out to compare the optimal settings by these two methods. SEM analyses of the weld cross-sections also have been performed to determine a quality lobe.

2. Experimental procedure

2.1. Equipment and materials

The spot welding experiments were performed with a Telsonic® lateral drive welding machine which provides a maximum power

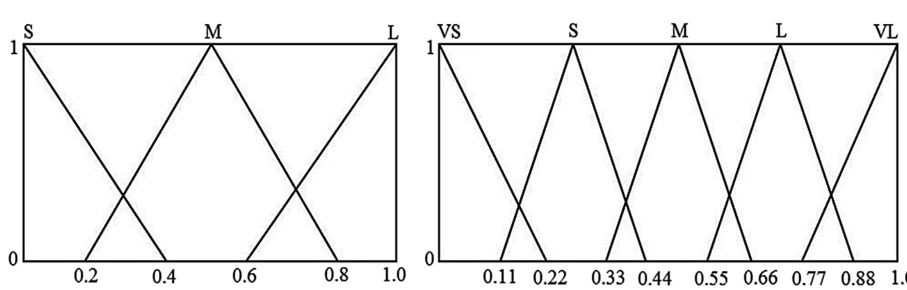

Fig. 7. Membership functions for individual responses and FMPI.

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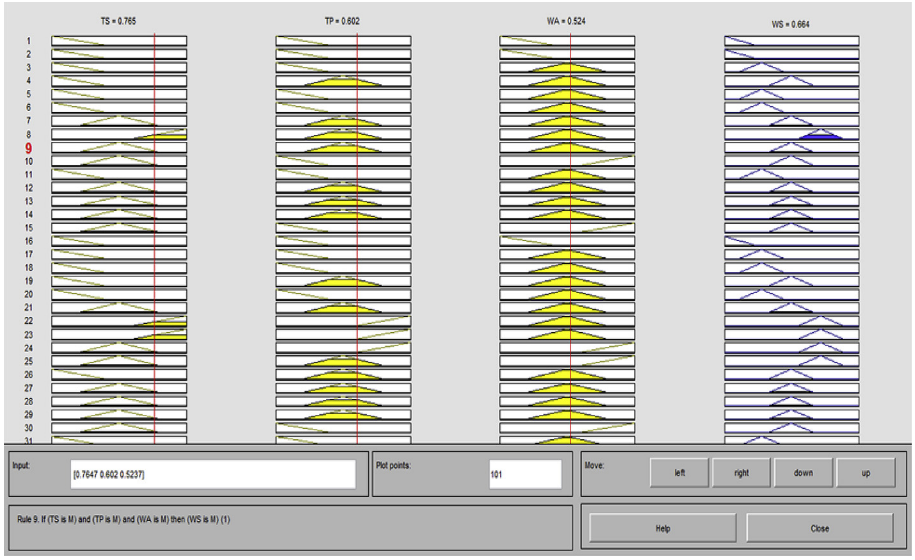

Fig. 8. Fuzzy logic reasoning procedure for the first run.

Table 5
Main effects on FMPI values.

Factors	Levels					Difference	Rank	Optimum level
	1	2	3	4	5			
A	0.400	0.500	0.610			0.210	3	A3
WP	0.350	0.640	0.530			0.290	1	WP2
WT	0.350	0.510	0.540	0.610	0.520	0.260	2	WT4

of 3 kW and a vibration frequency of 20 kHz. The ultrasonic horn with a knurled and flat welding tip of 11 mm × 9 mm has been employed for this study. It is made up of D2 steel because it offers high wear resistance and low acoustic losses, thus it acts as a tool for offering a good overall performance. The maximum peak-to-peak amplitude of the tip was 68 μm without any load. This is called as the maximum working amplitude. The two materials were clamped between this tip and a jig and one support is provided with it to fix both base metals. The schematic diagram is given in Fig. 1. The tensile shear stress (TS), T-peel stress (TP) and weld area (WA) have been deliberated for the evaluation of welding performance. All these performance characteristics were correlated with input parameters. So, proper selection of input factors with its range is highly needed for getting desired outputs.

In microelectronics industry as well as in small scale industries, aluminum and brass are the most commonly used material for fabrication work and also to produce solder free joints. For these reasons, these two materials have been chosen for this study. The welding experiments were carried out on 0.3 mm thick dissimilar materials like AA1100 aluminum sheet of grade H16 and UNS C27000 brass sheet of grade H04. The chemical composition of these two materials is represented in Table 1. For each weld trial, two coupon configurations were involved in the static tests: lap shear and T-peel. The specimen design with dimensions and fixture

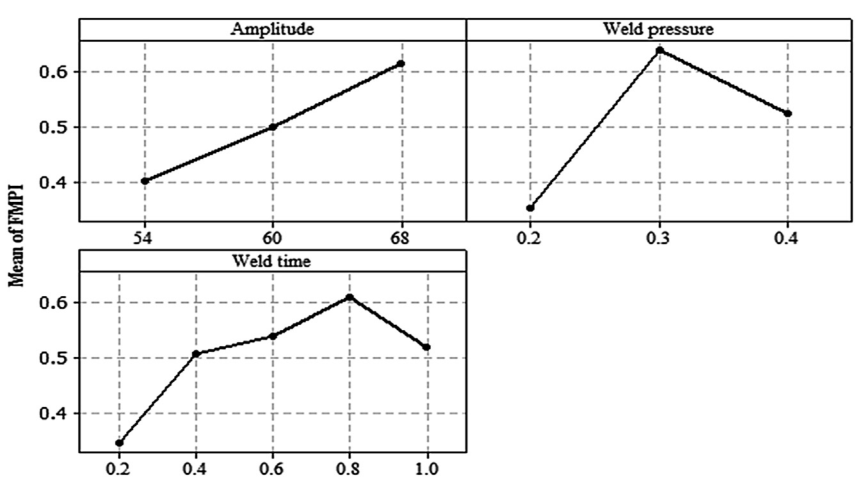

Fig. 9. Main effects plot for FMPI.

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Table 6
ANOVA results for FMPI.

Source	Sum of squares	df	Mean square	F value	p-value	
Model	1.30	6	0.22	69.28	<0.0001	Significant
A–A	0.34	1	0.34	107.44	<0.0001	
B-WP	0.22	1	0.22	70.56	<0.0001	
C-WT	0.18	1	0.18	58.70	<0.0001	
BC	0.018	1	0.018	5.89	0.0201	
B^2	0.40	1	0.40	127.78	<0.0001	
C^2	0.14	1	0.14	45.30	<0.0001	
Residual	0.12	38	3.120E-003			
Cor total	1.42	44				

design are shown in Figs. 2 and 3. Just before welding, the surfaces of the base metals were degreased and oxide free by the help of swabbing with acetone. This process is necessary in order to get a satisfactory weld.

2.2. Identification of control factors

The ultrasonic welding involves a number of process parameters which can influence the welding performance characteristics. From numerous literature studies and experimental trials, three important parameters as weld pressure (P), weld time (T) and vibrational amplitude (A) have been selected. The working range of each one has been selected in such a way that, the good welding can be obtained in that range and it has been found from trial experiments. In this current analysis, weld pressure and weld time have been divided into three levels each and the vibration amplitude has been varied in five levels. These factors with their level values are shown in Table 2.

Table 7
Input parameter search ranges.

Input parameters	Search ranges
Amplitude (A) (μm)	54–68
Weld pressure (WP) (MPa)	0.2–0.4
Weld time (WT) (Sec)	0.2–1.0

2.3. Experimentation and data collection

To investigate the influences of all input variables on the responses, the full factorial design of experiment was chosen. It is a

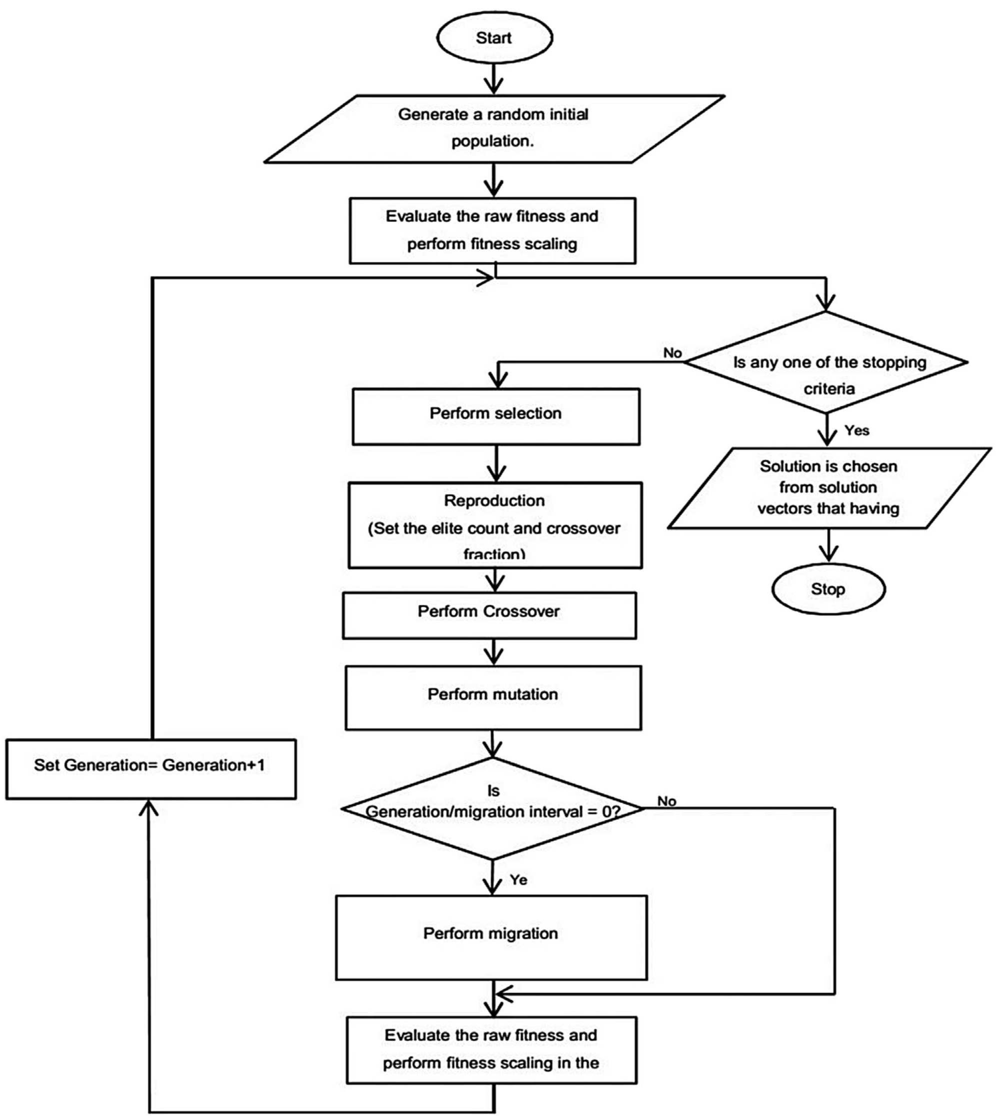

Fig. 10. Flow chart of GA.

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Table 8
Parameter settings for GA optimization.

Types of operation and parameter	Functions or parameters value used
Population	
a. Size	150
b. Creation function	Feasible population
Fitness scaling	Rank
Selection	Stochastic uniform
Reproduction	
a. Elite count	2
b. Crossover fraction	0.8
Cross over	Scattered
Mutation	Adaptive feasible
Migration	
a. Direction	Forward
b. Interval	20
c. Fractional	0.2
Stopping criteria	
a. Generation	100
b. Stall generation	50
c. Functional tolerance	1×10^{-6}

useful design because it allows the effects of a factor to be estimated at various levels of other factors and can yield the conclusions about the validation of these factors over a range of experimental conditions. In the meantime, specific considerations are taken to the repetition of experiments as it decreases the variability in experimental results and expands their significance and liableness. This is one of the scientific techniques which help to boost the confidence level of a welder to reach conclusions about an experimental variable [22]. So, using this design, the number of experimental runs was 45 with six replicates for each test condition. A total of 270 samples were prepared and out of which, 135 samples were for tensile shear test and 135 samples for T-peel test. Selected design matrix and experimental data are shown in Table 3. These tests were carried out at room temperature using a computerized universal testing machine INSTRON 1195. The samples after testing are shown in Fig. 4. To determine the trend of rising of temperature at the welding zone; the instantaneous interface temperature was measured in real time by K-type thermocouples. Fig. 5 shows the complete set up of welding machine with data acquisition system (DAQ). After welding, transverse sections of the weld coupons have been cut from the parent material and polished with different grades of emery paper and sylvet cloth followed by etching process. This is necessary to analyze the microstructure of the weld zone.

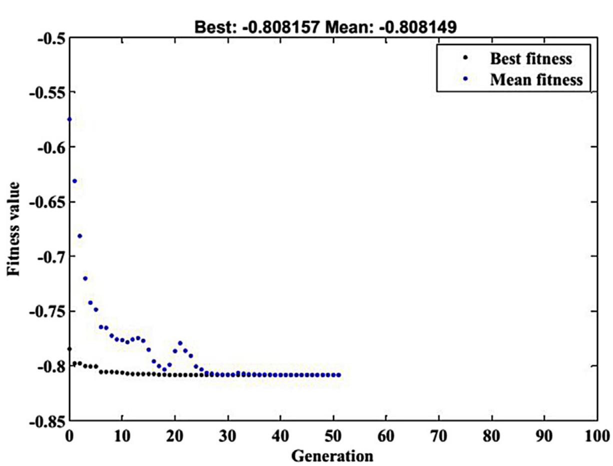

Fig. 11. Convergence plot of GA.

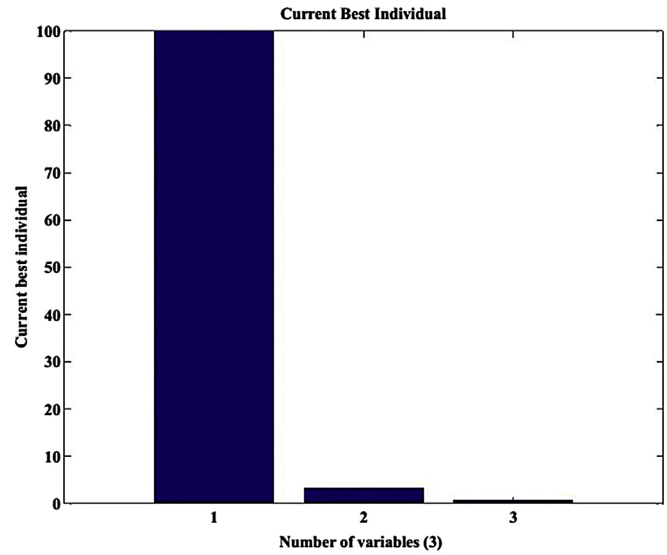

Fig. 12. Best individual parameter in GA optimization.

3. Methodologies

3.1. Fuzzy logic approach

Fuzzy logic is a mathematical theory of inexact reasoning, which allows the modeling of the reasoning process of human in linguistic terms. The fuzzy logic control allows the existence of uncertainty in handling parameter values [16,23]. Fuzzy logic system (Mamdani system) is mainly consisting of three important models during its development like fuzzifier, knowledge based inference engine, and defuzzifier [24], as shown in Fig. 6. The fuzzifier uses membership functions to fuzzify the normalized values of each performance characteristic. Next, the inference engine (Mamdani fuzzy inference system) performs fuzzy reasoning on fuzzy rules to generate a fuzzy value. Finally, the defuzzifier converts fuzzy predicted value into a single fuzzy multi performance index (FMPI). This process was repeated for all the experimental runs and respective FMPI value was found out. In this technique, there is no need to check the correlation and assigning weightage to the responses.

The different steps used in this methodology are

Step 1: To remove a certain degree of uncertainty and elusiveness, the responses are normalized. Another reason behind the normalization process is that the membership function (MF) curve depends on the mapping of input variables in its range of 0–1. In this computation, Higher-the-better (HB) criterion has been chosen for all the three quality characteristics. The formula used for HB criterion was

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{1}$$

where $x_i(k)$ and $y_i(k)$ are the normalized data and observed data respectively, the smallest and largest value of $y_i(k)$ are $\min y_i(k)$ and $\max y_i(k)$ respectively for *kth* responses

Step 2: The objective of this analysis is to simultaneously maximize TS, TP and WA. The Mamdani inference engine receives all the individual normalized values as the input and FMPI values are generated according to the membership functions and fuzzy rules using MATLAB. Thus the optimum condition of

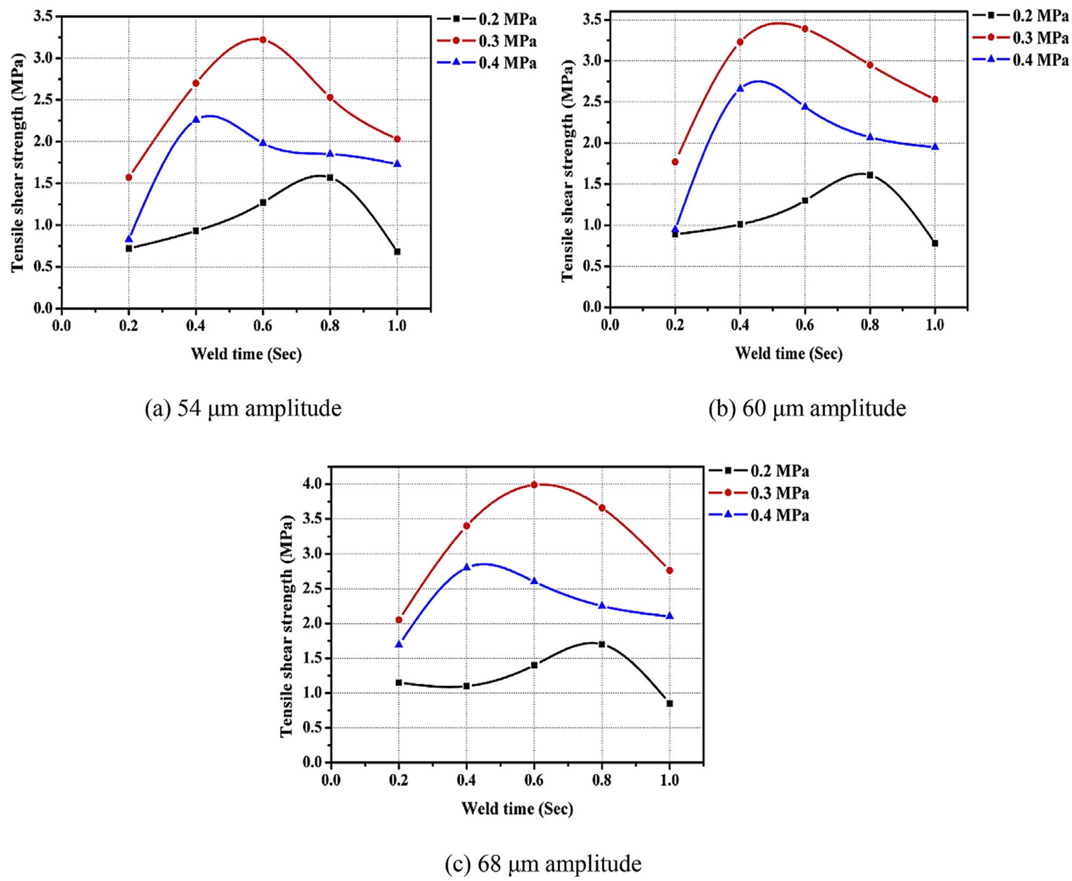

Fig. 13. Relationship between tensile shear stress with different process parameters.

the process parameters can be obtained by maximizing the FMPI. The results are shown Table 3.

Step 3: Fuzzy value of the quality characteristics is defined by the membership function. In this analysis the input and output variables are expressed in terms of linguistic variables. Fig. 7 shows the graphical representation of three fuzzy subsets like small (S), medium (M) and large (L), which is assigned to inputs (normalized responses) and five fuzzy subsets like very small (VS), small (S), medium (M), large (L) and very Large (VL) is assigned to FMPI. The fuzzy rules with different linguistic values and their fuzzy intervals are shown in Table 4. Various degrees of membership of the fuzzy sets are calculated based on the values of x_1, x_2, x_3 and Y. The relationship between three inputs and the output were represented in the form of if-then control rules that is:

Rule 1: if x_1 is Small, x_2 is Small and x_3 is Small then Y is Very small else

Rule 2: if x_1 is Small, x_2 is Medium and x_3 is Small then Y is Very small else

………………………………………………..

………………………………………………..

Rule n: if x_1 is Large, x_2 is Medium and x_3 is Large then Y is Very large else.

Mamdani implication is used to evaluate each rule and in this operation, the minimum memberships of various fuzzy sets are taken into account [25]. Mathematically, it is represented as:

$$\mu_{AB(x,y)} = \min\left[\mu_{A(x)}, \mu_{B(y)}\right] \tag{2}$$

where $\mu_{A(x)}, \mu_{B(y)}$ are the membership functions of different fuzzy sets respectively.

The results of all rules are further combined to give rise a final output called as aggregated fuzzy output and it is expressed as

$$\mu_y = \mu_{A(x1)} + \mu_{A(x2)} + \mu_{A(x3)} + \cdots + \mu_{A(xn)} \tag{3}$$

These final fuzzy output values can be obtained in linguistic terms, when the fuzzy implication and fuzzy aggregation are united. The fuzzy logic reasoning is shown in Fig. 8. In this study, for each rule, the three inputs are assigned in the fuzzy subsets and the first three columns represent it. The number of rules yielded from the present study is 45.

Step 4: Finally, the defuzzifier converts the fuzzy output into a non-fuzzy absolute value called FMPI. Center of gravity, the most popular method is adopted in this study to transform the fuzzy inference output μ_y into a non-fuzzy value Y_0, which is also known as the crisp output. The last column of the same Fig. 8 shows the defuzzified value. It is calculated with the help of the following equation

$$Y_0 = \frac{\sum_{i=1}^{45} x^*\left[\mu_y\right]}{\sum_{i=1}^{45}\left[\mu_y\right]} \tag{4}$$

Step 5: The relative importance amongst the welding parameters need to be known for getting the highest value of FMPI. For this, the optimal combination of the input parameter levels can be determined more accurately by the calculation of

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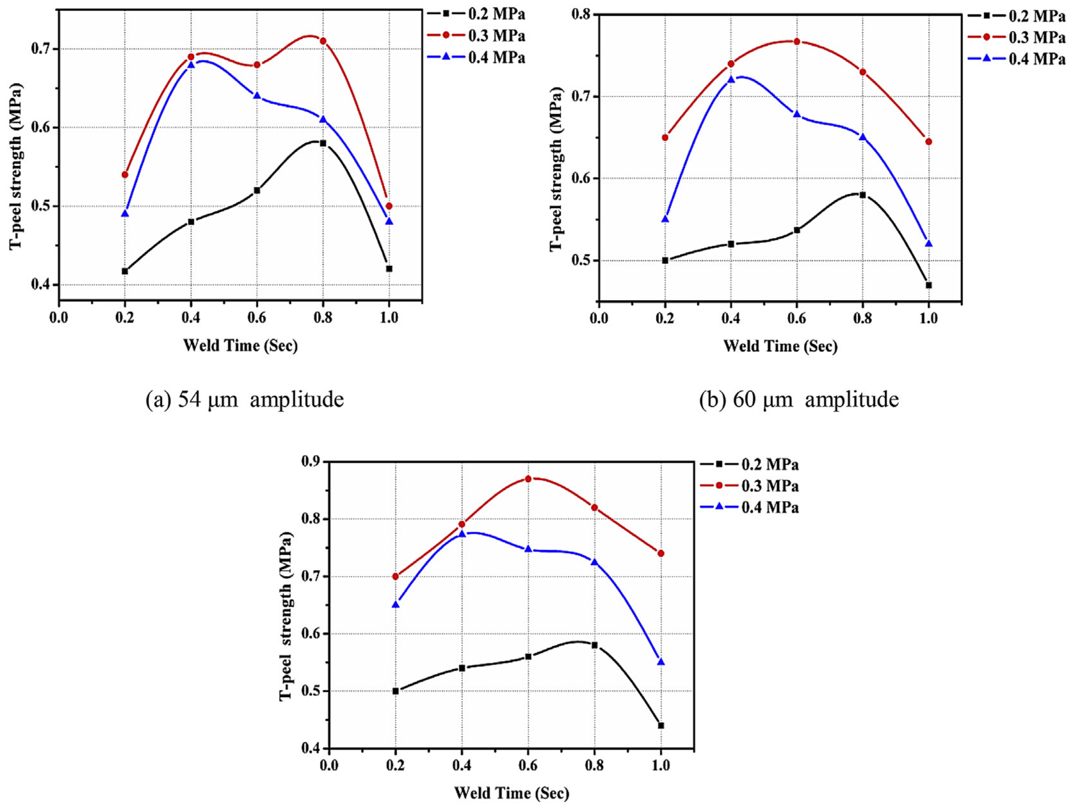

(a) 54 μm amplitude (b) 60 μm amplitude

(c) 68 μm amplitude

Fig. 14. Relationship between T-peel stress with different process parameters.

average FMPI values. The rank also shows the influence of each parameter in the response and as the amplitude is at rank 1, it influences most among other parameters. So, based on the above discussion, larger the FMPI, smaller is the variance of the performance characteristics around the desired value. The main effects of the factors are computed and are shown in Table 5 and graphs are also plotted in Fig. 9. From it, the best combination of process variables is A (68 μm), WP (0.3 MPa) and WT (0.8 Sec).

3.2. Development of mathematical model

As USMW is a nonlinear process, for the accurate prediction of the response, a second-order model has stated for getting a relationship between process parameters and the response. It can be expressed as [26] FMPI = f (A, WP, WT) where FMPI i.e. obtained from fuzzy logic concept is considered as the response or yield. The equation which used to find out this second order polynomial model is given by

$$Y = b_0 + \sum b_i X_i + \sum b_{ii} X_i^2 + \sum b_{ij} X_i X_j \tag{5}$$

where b_0 is the average of all responses, b_{ii} and b_{ij} are the coefficients for main and interaction effects.

All the calculation of coefficients and analysis of data were performed using Design-Expert 8.0.1. In this analysis, all the coefficients are analyzed at 95% confidence level. The insignificant coefficients were removed by the back elimination technique without affecting the accuracy of the model [27]. The final mathematical model developed to predict the FMPI for the ultrasonic welding is given below

$$\begin{aligned} FMPI = {} & -2.854 + 0.015 \times A + 13.361 \times WP + 1.492 \times WT \\ & - 0.875 \times WP \times WT - 19.966 \times WP^2 - 0.837 \times WT^2 \end{aligned} \tag{6}$$

For checking of the current regression model, R^2, adj. R^2 and the standard error results are computed from the ANOVA analysis and are presented in Table 6. It shows the P-value for the model is less than 0.05 at the described confidence level. So, it indicates that the model is a significant one. As the multiple regression coefficient (R^2) value is 0.9162, the predicted response values will adequately match with the experimental results. It shows the fitted model can explain the variation in FMPI up to 91.62%.

3.3. Genetic algorithm approach

Motivated from Darwin's theory of evolution, Genetic algorithm has been used as a standard tool for producing global and optimized solutions to the problems. This is a population based heuristic technique and was first introduced by Holland in 1975 [28]. This evolution starts with the generation of random population and chromosomes. The stochastic uniform selection procedure is generally used to select these chromosomes and then crossover and mutation operations are performed on it. Then for each individual, fitness value is evaluated in a population and compared with other best value present and changed according to it. The repetition of the process continues until it reaches the stopping criteria i.e., number of generations [29]. The main purpose of using this algorithm is to

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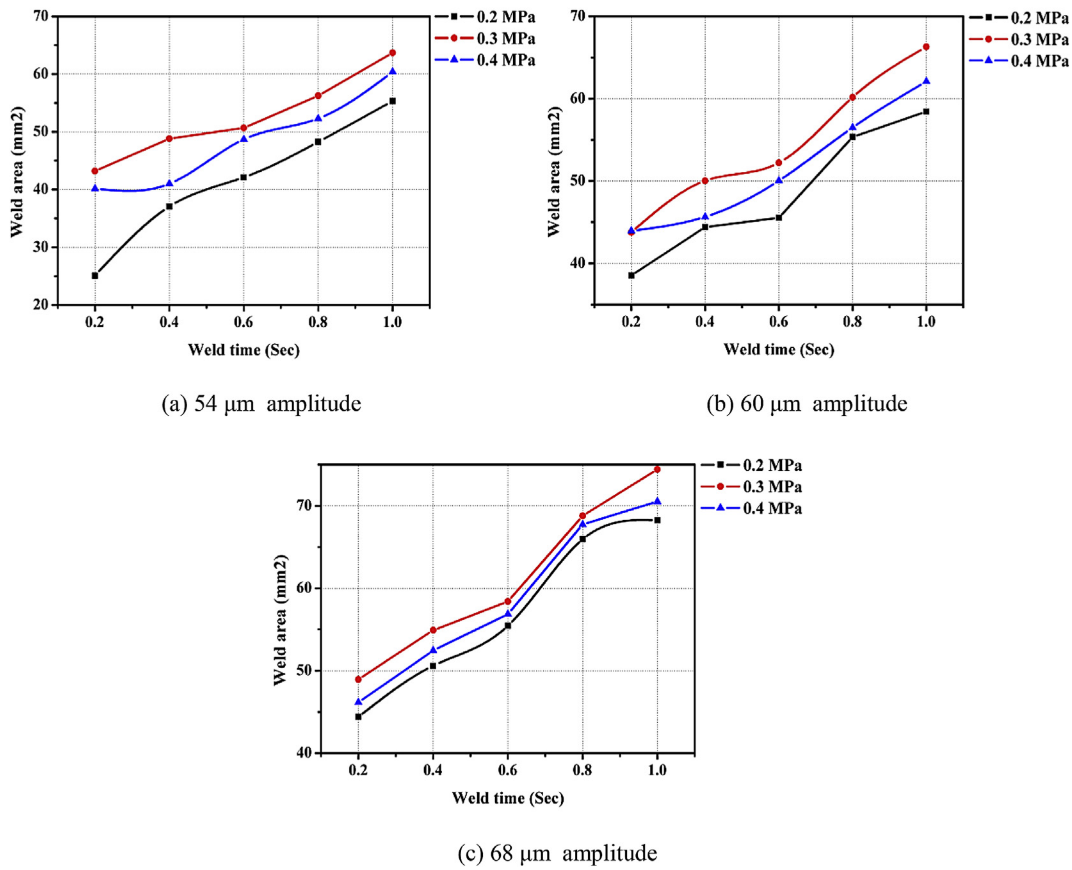


Fig. 15. Relationship between weld areas with different process parameters.

develop a model which will maximize the FMPI value. The flow chart of this process is presented in Fig. 10.

The biggest advantages of GA are that it will operate in a huge continuous domain, rather than a discrete point and its results will not be affected by the presence of any discontinuities in the objective function. But the other part of it is that it will require more computational effort than any conventional technique. The optimization tool box of Matlab® has been applied to maximize the stated objective function as presented in Eq. (6) using the different process parameters. The possible search ranges of the control parameters in which the objective function gives the maximum value is given in Table 7. Different functions and parameters setting in the tool box that have been used in this study have been listed in Table 8.

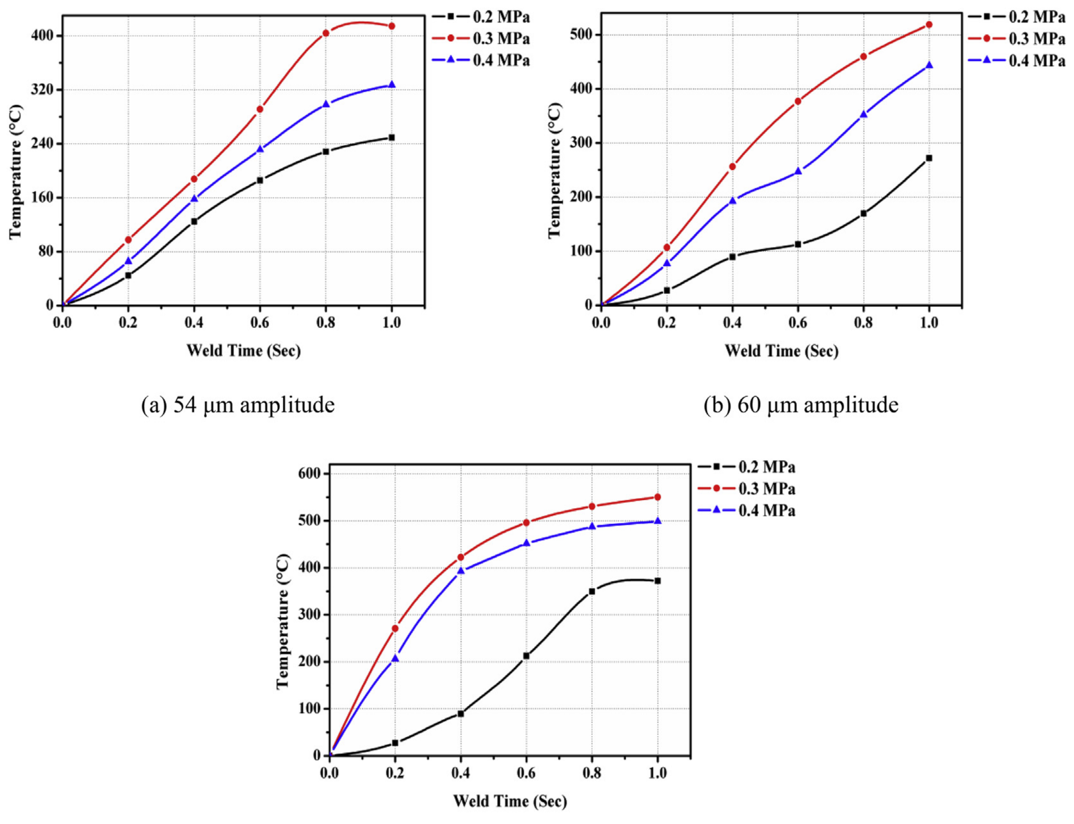
A double type random population was first initialized. Then rank scaling function was used to convert the raw fitness scores and that are a return of the fitness function. The members were called parents and they were selected by using the stochastic uniform function. The elite count and crossover fraction were specified in reproduction options to create children for the next generation. These elite children can be defined as the individual in the current generation with best fitness values. Migration operation was performed to introduce the movement of individuals between subpopulations and it was based on the condition that, the population size has to be set as a vector of length of greater than 1. This operation can be controlled by three parameters like migration direction, migration interval and migration fraction and also in this operation the best individuals from one subpopulation replace the worst individuals in another subpopulation. After all these operations, the current population was replaced with the children to form the next generation. The algorithm stopped when it met the specified number of generations as the stopping criteria. The more details about this algorithm can be referred from the global optimization tool box [30].

The optimization was continuously monitored throughout the generations. The best fitness and mean fitness from generation to generation was recorded in the form of fitness plot and shown in Fig. 11. From this plot, it can easily observe that, the fitness value is converging towards the optimal from one generation to another generation. Vector entries of individuals with the best fitness function value were represented in Fig. 12. From this graph, the optimum condition of the process parameters have been found out i.e. amplitude of 68 μm, weld pressure of 0.4 MPa and weld time of 1 Sec.

4. Results and discussion

4.1. Effect of process parameters on tensile shear stress

Fig. 13(a) to (c) shows the tensile shear test results with respect to various parameter conditions. From these figures, it clearly signifies that, the maximum tensile shear stress can be achieved at a moderate amount of weld pressure (0.3 MPa) and weld time (0.6 Sec). After 0.6 Sec, the strength tends to decrease because the cracks are formed around the weld zone of aluminum sheet. For the lower clamping pressure like 0.2 MPa, it takes a slightly longer time period to reach its optimum value. The possible reason behind this is that, the oxide layer may not be broken at short welding period of time and thus the formation of micro bonds may not happen. For high clamping force like 0.4 MPa, the strength



(a) 54 μm amplitude

(b) 60 μm amplitude

(c) 68 μm amplitude

Fig. 16. Measurement of temperature at interface with respect to different process parameters.

decreases even if the welding time is high. This is because, at a higher pressure, the relative motions between the sheets are ceased. Thus, the dissipation of energy and formation of micro bonds could not happen. The other reason for this behavior is the occurring of the interfacial lock at the weld interface and the heat which is generated due to it, breaks the bonds [31]. These natures of the weld pressure and weld time remain same for 54 μm, 60 μm and 68 μm amplitude. At 68 μm, the maximum value of 3.99 MPa has been obtained followed by 3.39 MPa at 60 μm and 3.22 MPa at 54 μm. This is because, at higher amplitude, the relative motion between the sheets increase and thus the more amount of heat is produced, which creates a favorable condition for the formation of bonds.

4.2. Effect of process parameters on T-peel stress

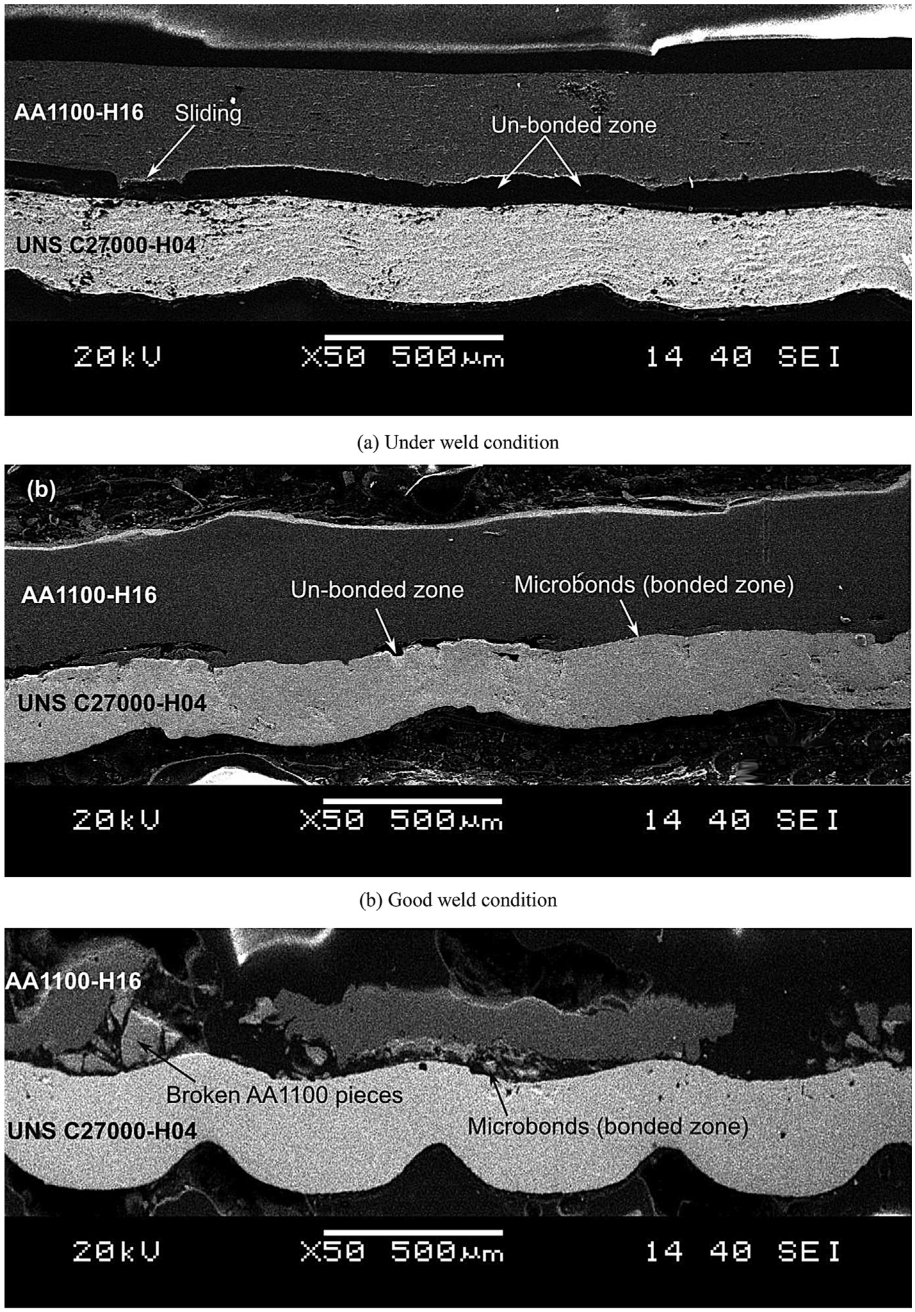
Similar to the tensile shear test of the weld samples, T-peel test also shows the same behaviour. It is presented in Fig. 14. In this case also, the maximum T-peel stress of 0.87 MPa is achieved at 68 μm amplitude, followed by 0.76 MPa at 60 μm and 0.71 MPa at 54 μm. But one noticeable point is, at 54 μm amplitude, it takes a little bit longer period of time (0.8 Sec) than a tensile shear test to reach its optimum value. As described earlier, the reason behind this is the relative motion, which is less at this amplitude and thus, the formation of heat may not be so much to form the micro bonds. However, in most of the T-peel samples, interfacial fractures as well as a combination of interfacial fracture and nugget pull-out were mostly noticed. In some of the samples, the tearing of the aluminum sheet was happened after the nugget pull-out.

4.3. Inspection of weld area

A comparison of the weld areas is shown in Fig. 15. In this present study, the point contacts have been made between these sheets, small micro bonds initially develop and gradually increase with all the input parameters except weld pressure which, has to be increased up to a particular value. Because at a higher welding time and vibration amplitude, the generation of temperature is more which, results the more formation and saturation of micro bonds and thus, it is very difficult to measure this real weld area. Therefore, instead of finding real weld area, an average or general weld area is calculated by the multiplication of one micro bond area with no. of points present on the horn tip. But when the welding pressure is increased beyond a certain value, the relative motion between the sheets disappears and interlocking happens. For this reason, the weld area has not grown so much at higher clamping pressure. The highest weld area of 74.42 mm^2 has been obtained at 68 μm amplitude, followed by 66.30 mm^2 at 60 μm and 63.70 mm^2 at 54 μm.

4.4. Interface temperature measurement results

As the thermal conductivity of the brass is lower than aluminum, the interface temperature rises suddenly and it is the reason for high plastic deformation of the aluminum material. Therefore, the temperature measurements have performed and are presented in Fig. 16. USW happens in a fraction of time, it is difficult to gather a large amount of data regarding temperature [32]. To investigate the trend of temperature rise in the weld coupon, 0.1 mm diameter k-type thermocouple was implanted near to this



(a) Under weld condition

(b) Good weld condition

(c) Over weld condition

Fig. 17. SEM images of weld cross-sections for different weld qualities.

area. The curves show that, as the welding time increases, the temperature rises very quickly and reaches to a maximum value of 550.36 °C at 68 μm amplitude, followed by 518.36 °C at 60 μm and 414.27 °C at 54 μm. Thus, it signifies that, at higher amplitude, the weld zone was severely deformed and also rupturing of the oxide film also took place. Such temperatures are sufficient enough to make tensile shear stress, T-peel stress and weld area high.

4.5. Microscopic weld quality determination

The characteristics of a good weld include highly dense interfacial bonds with no gaps. It can be obtained from bond density attribute and it includes features like micro bonding, un-bonded region and swirls like pattern. SEM images along the cross-sections of "under", "good" and "over" weld conditions are shown in Fig. 17. In under weld condition, there is a gap between two materials and no micro bonds are found in this condition and in good condition, the welding interface is tightly packed with micro bonds. The bond density is high in good weld condition. The possible reasons behind these phenomena are, during under weld condition, due to the low value of all input parameters, sufficient friction may not have been developed in the mating surfaces. Thus, inadequate heat generation is insufficient for inter atomic diffusion. The weld strength (obtained tensile shear and T-peel stress) is mainly due to the mechanical interlocking. When the values of input parameters are increased, the amount of heat production is

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Table 9
Confirmation test results for multi objective optimization.

	Initial parameter setting	Optimal conditions	
		From fuzzy logic	From GA
Level	A2WP1WT4	A3WP2WT4	A3WP3WT5
Tensile shear stress (MPa)	1.6100	3.6600	2.1100
T-peel stress (MPa)	0.5800	0.8200	0.5359
Weld area (mm^2)	55.3500	68.8000	70.5441
FMPI	0.4500	0.9400	0.6120

also more at the interfaces. An effective bonding between two sheets is observed due to interatomic diffusion and it is treated as the good weld condition. But in over weld condition, there is no uniformity of aluminum material at the welding zone. In this condition, as the temperature increases, the sheets get to be more ductile and subsequently profound distortion or extrusion will happen in the top sheet by the sonotrode tip which is otherwise called sticking. As in this study, the aluminum is treated as the top workpiece and more ductile than brass, these are heavily deformed and broken into pieces due to high weld pressure, weld time and amplitude vibration. This may lead to the cracking failure of the weld at its edges.

4.6. Confirmatory test

After evaluating the optimal predicted parameter settings from fuzzy logic and genetic algorithm, then each response and FMPI values are compared with each other. These results are shown in Table 9. The tensile shear stress and T-peel stress obtained at the optimal setting of fuzzy logic are much better than the values obtained from the GA. But the weld area obtained from the optimal condition of GA is better than fuzzy logic. So, it is required to analyze both these methods on one final response, i.e. FMPI in such a way that one superior method can be distinguished over another. In this study, the FMPI value as 0.94 is achieved, which is better than the FMPI value of GA i.e. 0.61.

5. Conclusions

In the foregoing study, the weld runs are executed as per the full factorial design on an ultrasonic metal welding setup and the following points are gathered.

1. By using fuzzy rule based model, the multi responses like tensile shear stress, T-peel stress, weld area are taken as three inputs and combined into one response i.e. FMPI. The major advantages of this technique are individual priority weights need not to be assigned and the correlation of responses can be prevented.
2. Based on its main effects results, the most influencing parameter on the response is the vibration amplitude as it occupies rank 1 followed by weld time and weld pressure. An amplitude of 68 μm, weld pressure of 0.3 MPa and weld time of 0.8 Sec are the optimum inputs to get excellent weld using this method.
3. Further the FMPI data are used to develop a mathematical model using nonlinear regression equation and the ANOVA has also been performed to analyze the accuracy of the model with the experimental value. This model can explain the variation in FMPI up to 91.62%.
4. This mathematical model is used as the fitness function for GA and after tuning the different parameters, the optimum values of the process parameters are obtained. The biggest advantages of this technique are that it will operate in a huge continuous domain and its results will not be affected by the presence of any discontinuities in the fitness function. From the best individual plot results, amplitude is the most influencing parameter followed by weld pressure and weld time. The optimum conditions like amplitude of 68 μm, weld pressure of 4 bar and weld time of 1 Sec are obtained.
5. From experimental investigation, the maximum values for tensile shear stress, T-peel stress and weld area are obtained at 0.3 MPa weld pressure and at 68 μm amplitude. These values also increase with weld time up to a certain point and then decreased due to formation of cracks around the weld zone.
6. The interface temperature is also increased with the increase of input parameters. It is maximum at amplitude of 68 μm because of high relative motion between the sheets.
7. The microscopic analysis also has been done to create a quality lobe of welding like “under weld”, “good weld” and “over weld”. These are differentiated from each other with respect to the formation of micro bonds and absence of gaps.
8. Lastly, a comparison between fuzzy logic and genetic algorithm techniques is done in this work to show which technique accurately optimizes the process parameters to get the maximum FMPI value. Observations indicate that the fuzzy modeling results a high FMPI value than GA. So, fuzzy technique could be an economical and better method for prediction of quality characteristics with respect to the process variables.

Acknowledgement

The authors gratefully acknowledge the support provided by Centre for Council and Industrial Research (CSIR), Govt. of India (Grant no. 22 (0593)/12/EMR-II dated 2.4.2012) to carry out this research work.

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